Guides for
Electric Cooperative Development and Rural Electrification

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Your Touchstone Energy® Partner

Glossary of Abbreviations

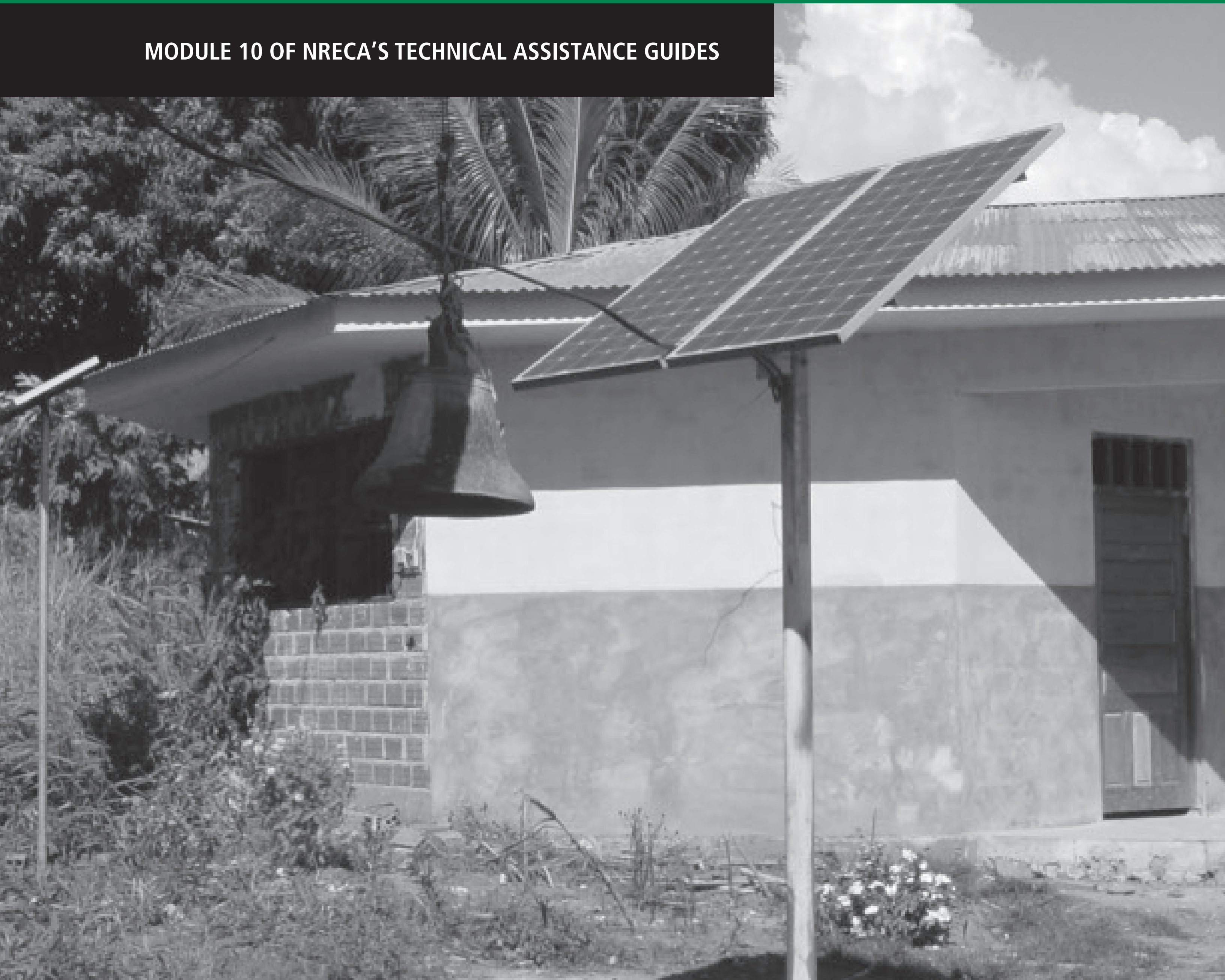
A	Ampere
AH	Amp-hour
AC	Alternating current
ACSR	Aluminum conductor, steel reinforced
A&G	Administrative and general
AWG	American wire gauge
CARES	Central American Rural Electrification Support Program
CCT	Correlated color temperature
CDA	Cooperative Development Authority (Philippines)
CEF	Fronteriza Electric Cooperative (Dominican Republic)*
CFC	National Rural Utilities Cooperative Finance Corporation, also known as NRUCFC (U.S.)
CFL	Compact fluorescent light bulb
CLARITY	Cooperative Law and Regulation Initiative
CONELECTRICAS	National Consortium of Electrification Companies of Costa Rica (Costa Rica)*
DC	Direct current
DISCEL	Electric Distributor of the Hydroelectric Executive Commission of Rio Lempa (El Salvador)*
EBIT	Earnings before interest and taxes
EBITDA	Earnings before interest, taxes, depreciation and amortization.
EEGSA	Electric Company of Guatemala, PLC (Guatemala)*
ESMAP	Energy Sector Management Assistance Program (World Bank)
FUNDAP	Foundation for Economic Development
G&T	Generation and transmission cooperative
GIS	Geographic information system
GPS	Global positioning system
HVD	High voltage disconnection
I	Electrical current, measured in amperes
ICE	Costa Rican Institute of Electricity (Costa Rica)*
IEC	International Electro-technical Commission
INDE	National Institute of Electrification (Guatemala)*
INE	National Institute of Statistics (Bolivia)*
IRR	Internal rate of return
ISPRA	National Institute for Protection and Environmental Research (Italy)
K	Kelvin
klmh	Kilo-lumen hour
kV	Kilovolt
kVA	Kilovolt-ampere
kVAR	Reactive kilovolt-ampere
kW	Kilowatt

kWh	Kilowatt hour
LED	Light-emitting diode
LPG	Liquefied petroleum gas
LVD	Low voltage disconnection
LVR	Low voltage reconnection
MRT	Single wire earth return*
MW	Megawatt
MWh	Megawatt hour
NEA	National Electrification Administration (Philippines)
NESC	National Electrical Safety Code
NGO	Non-governmental organization
NOAA	United States National Oceanic and Atmospheric Administration
NPV	Net present value
NRECA	National Rural Electric Cooperative Association International, Limited
OCDC	Overseas Cooperative Development Council
O&M	Operations and maintenance
PDB	Power development board
PUC	Public utility commission
PUE	Productive use of electricity
PV	Photovoltaic
PWM	Pulse width modulation
R	Electrical resistance
R&D	Research and development
RE	Rural electrification
REA	Rural Electrification Administration, an agency of the Department of Agriculture of the United States, now known as RUS
REB	Rural Electrification Board (Bangladesh)
RFP	Request for proposal
RFQ	Request for quote
ROE	Return on equity
RUS	Rural Utilities Services, an agency of the Department of Agriculture of the United States, previously known as REA
SWER	Single wire earth return
TAG	Technical assistance guide
UL	Underwriters Laboratory
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USTDA	United States Trade and Development Agency
V	Volt
W	Watt
WH	Watt-hour
Wp	Watts peak
WtP	Willingness to pay

*English translation of Spanish abbreviation

Design and Implementation Guidelines for Stand-Alone Solar Photovolatic Systems for Rural Electrification

MODULE 10 OF NRECA'S TECHNICAL ASSISTANCE GUIDES



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EXECUTIVE SUMMARY

This module was developed for institutions and individuals involved in the promotion, design, and implementation of stand-alone solar photovoltaic (solar PV) rural electrification projects. Its concepts and guidelines allow the reader to evaluate a project's technical and financial feasibility, project beneficiaries (i.e. energy demand), and factors affecting solar PV system component performance (e.g. solar irradiance, site geography, energy supply constraints, etc.). Readers will then be able to finalize system design and component selection for optimal system cost and performance. The solar PV design parameters and methodologies presented here also allow project practitioners to understand system operation and maintenance issues, an often overlooked necessity for the proper management of these systems in rural electrification applications.

Renewable energy technologies for remote power supply are particularly appropriate for use in rural areas where grid-based electric service is not financially feasible. In most cases, the implementation of small-scale renewable energy systems occurs in areas of low population density, and low energy demand, where there is nevertheless sufficient income potential to assure the recovery of project costs (capital and/ or operating and maintenance costs).

While many technology options can feasibly provide remote energy service to isolated communities, the most practical and lowest cost solutions are normally quite limited. Limiting factors include resource availability, delivered cost of fuel (for conventional fossil-fuel energy systems), and magnitude of demand for energy services. In addition, it is important to take into account operation and maintenance requirements (availability and cost), and the level of technical capacity (required versus available) to support after-installation service for these remote energy systems.

Sustainability of remote renewable energy systems requires the same, if not greater, level of discipline as conventional grid-based energy delivery systems. The following characteristics are essential for assuring project sustainability:

- Engineering design that addresses specific energy needs, while minimizing cost and technological complexity
- Robust institutional structure with dedicated leadership and technical, managerial and operational capacity for project operations and maintenance
- Mobilization of community members to promote a sense of ownership in the project, improve collections efficiency, and reduce maintenance costs for service providers
- Efficient and effective commercial systems to ensure sufficient cost recovery for operations and maintenance costs

In many countries, solar photovoltaic systems are the most promising renewable technology option for delivering modern energy services to rural consumers due to favorable climatic conditions, the energy needs of rural consumers, and their dispersed geographical distribution. Solar photovoltaic systems have been deployed for more than 20 years in a variety of rural, remote applications, with notable success within larger-scale programs. However, there have also been notable failures. Experience demonstrates that these programs require careful planning,

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extensive and detailed preparation, seamless coordination with communities and local political leadership, and very practical and effective management systems.

The project implementation cycle combines engineering and financial analysis, institutional design and community engagement. This module focuses on all phases of the project implementation and management cycle, including due diligence on the proposed project location, financial and technical analysis, project technical and institutional design, procurement and installation, maintenance, and overall management issues.

In many countries, solar photovoltaic systems are the most promising renewable technology option for delivering modern energy services to rural consumers.

INTRODUCTION

This module serves as a reference for electric cooperatives, technicians, social scientists, and institutions involved in the design and implementation of stand-alone solar PV rural electrification projects. It presents concepts and guidelines that allow the reader to evaluate and make informed decisions concerning project design and feasibility, technology selection, system design, and implementation, as well as to operate, maintain, and manage solar PV systems for rural residential applications.

The module begins with a brief summary of the conceptual framework behind the application of stand-alone solar PV systems in rural electrification. Following the conceptual framework are guidelines on project design, implementation and operation, solar PV design parameters and specifications for system components and, finally, the use and operation of a stand-alone solar PV system and its components.

Because issues related to installation, operation and maintenance practices have challenged the sustainable use of many solar PV projects, this module proposes guidelines to reduce the risks that threaten successful implementation and long-term operation of these projects.

For the most part, the target communities participating in solar PV projects are located in areas distant from grid-based electric service, sometimes in areas quite remote from major population centers. Often, the residents of these communities rely on marginal financial resources, with uncertain incomes and earning potential. As always, finding the means to deliver modern energy services to lower income communities presents specific challenges, requiring deployment of least-cost energy solutions to facilitate the lowest possible recurring costs to project beneficiaries.

CONCEPTUAL FRAMEWORK

The process of increasing access to rural electric service is complicated by the requirement to match the cost of providing the service with the beneficiaries' ability to pay for service. By definition, rural area population density is lower than in urban or peri-urban areas. Moreover, economic opportunities are often more limited than in areas with higher population densities. These two factors usually result in higher costs to deliver commercial energy service and lower revenue potential for energy service providers. The challenge of establishing and sustaining energy services that are appropriately priced, with reasonable reliability, often hinges on the technology selected, and the concurrent amount of energy made available to the community beneficiaries.

Properly designed rural electrification programs take a technology-neutral orientation. While the design of programs should maximize the economic impact of their investments, they must also balance this goal with assuring that the service provided is affordable and the delivery vehicle sustainable. That is, the energy service must meet the needs of the community served while assuring that the cost of operating the energy system can be recovered from the beneficiaries of the service.

Grid-based electric service has historically served as the primary means of delivering rural energy service. With advances made in lower-cost, more reliable renewable energy technologies, and particularly with solar PV panels, it has become possible to offer an alternative to grid electric service. Given the distances and low population density of some rural areas, there are numerous communities that are not, and may never be, practical candidates for the extension of the electric grid. These communities are typically difficult to access, characterized by dispersed housing clusters, often with low income potential and low rates of energy use. Such communities are not likely to receive grid electric service in the near or medium term. Alternate models and modalities of providing electric service are needed to offer an inclusive energy service strategy for these communities.

Considering the lower income levels that most often characterize remote communities, and overlaying the need to assure that projects can achieve financial sustainability, it is necessary to assure that adequate steps are taken to enable target communities to obtain the resources necessary to pay for the cost of service – even if the beneficiaries are expected only to pay for operation and maintenance expenses. This means that an integral part of the project development cycle must include an analysis of the ability and willingness to pay for service and concurrently to estimate the levels of energy consumption and demand of the target population. The project preparation process should also evaluate service provider options and how payments will be collected from the beneficiaries to satisfy operating and maintenance expenses.

Renewable Energy for Rural Electrification

As explained above, renewable energy systems are particularly useful for remote areas that cannot be economically served via grid extension. Such areas have low population density and dispersed housing, resulting in low demand density. Renewable energy systems can be deployed in those areas either as micro systems (such as stand-alone solar systems) or as small or mini-grid distribution systems. To serve these more remote areas, there exists a variety of energy delivery systems, each characterized by fuel type, capital cost, energy delivery capacity, level of expertise required for installation and maintenance, and operating cost. Selection of the most appropriate technology often depends on two primary factors: energy required and total delivered cost of service.

Most rural electrification projects are not attractive financial investments. Even areas that can be economically served with grid electric service often require capital subsidies. Rural areas that can be served only with renewable, off-grid technologies also pose significant challenges to long-term financial viability and generally require a combination of capital subsidies and longer-term support for service provision.

Properly designed rural electrification programs take a technology-neutral orientation.

The design of financing programs to address the divergence between capital cost and ability to pay for service is one of the key barriers to overcome to expand access to renewable energy systems for rural electrification. Developers can meet this challenge by channeling funds through a special project financing facility, by establishing special financing windows in existing infrastructure development or rural development credit facilities, or by creating a special program within an existing rural electrification program management agency. In economically fragile communities, financing issues must be carefully analyzed to find practical solutions that facilitate improved access to electric service. The more accessible and practical the financing mechanism, the less problematic program implementation is likely to be.

Why Choose a Solar Photovoltaic System?

Stand-alone solar photovoltaic systems for residential use represent an increasingly attractive option to meet basic electricity needs of remote communities. The last decade has seen an explosion of solar PV systems installed in a number of large and expanding rural electrification programs.[1] Significant programs have been deployed in Bangladesh, India, East Africa, Morocco, Tunisia, Afghanistan, and China, among other countries.

Use of solar PV systems is most appropriate in those areas where housing density is low, and where energy demand is limited to lighting, communications, and entertainment (usually just radio and television service). These energy needs can be met by the use of what has been called a stand-alone "solar home system" (SHS), a very basic energy supply system comprising a solar PV panel, a charge controller, and a battery to store energy generated by the PV panel. The installed cost of these systems varies according to panel and battery capacity, as well as labor and transport costs. While the costs have decreased marginally in recent years, solar PV systems are still too expensive for all but the most economically advantaged in rural areas. They have and continue to require capital subsidies to achieve notable market penetration.

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Several important characteristics govern successful implementation of a solar photovoltaic electrification project:

- *Simplicity:* Design of solar PV systems must result in minimum maintenance requirements.
- *Modularity:* Solar PV systems are modular in nature. Considering this, the project design should offer two or more system options to facilitate higher levels of service for those families that may have the means to pay for the increased cost of service.
- *Environmental aspects:* A photovoltaic system does not produce carbon dioxide or other greenhouse gases, and does not otherwise generate environmental pollution. Due to the fact that most solar PV systems employ lead acid batteries, retrieval and recycling programs need to be incorporated in the program to assure that the disposal of batteries does not result in environmental impact.
- *Maintenance:* All energy systems require maintenance, and solar PV systems are no exception. However, maintenance requirements can most often be performed in whole or in part by locally trained technicians. Solar PV systems rarely require highly skilled technicians.
- *Durability:* Solar PV panels have a rated life expectancy of 20 years. Batteries, charge controllers, and lamps have considerably shorter life expectancies. Properly used and maintained flooded batteries have life expectancies of 2-5 years, with longer life expectancy for deep-discharge batteries, and shorter for lead antimony batteries designed for automotive applications.
- *Cost:* As mentioned above, solar PV systems vary in cost according to the size of the panel, battery, wiring/lighting system, and local labor cost. Maintenance and operating costs are normally minimal in comparison to capital costs, assuming that with minimal training, local technicians can provide post-installation service. Solar PV systems require battery maintenance and may require periodic charge controller repair or replacement. Costs can be as low as US$300 for a small, 20 Wp solar PV lighting system, to as much as US$1,000 for a 75 Wp system that provides power for four or more lamps, television, and radio (up to 600 watt-hours of energy per day).
- *Resource availability:* Unlike other renewable energy technologies of broad use (wind, biomass, and hydroelectric), solar energy is relatively homogeneous. Most areas have, at a minimum, four sun-hours of solar radiation per day (where one sun hour is equivalent to 1,000 watt-hours per meter).

[1]Energy Sector Management Assistance Program (ESMAP), *Energy Development Report 2000: Energy Services for the World's Poor* (Washington, D.C.: The World Bank, 2000).

PROJECT DESIGN, IMPLEMENTATION, AND OPERATION GUIDELINES

Successful solar PV project implementation means more than ensuring properly functioning systems during the initial year after installation or during the limited life span of the batteries and charge regulators. The ultimate goal for any solar PV project should be sustainability of energy services over the useful life of the solar PV panels themselves.

Several factors contribute to project sustainability. First and foremost, it is important to specify and procure high-quality system components and to assure that they are properly installed. This requires careful design and management of the project implementation process. This should include a clear and transparent procurement process, verification or pre-qualification of the vendors who sell and install the solar PV systems to ensure that they have the requisite knowledge and skills. It also requires sufficient oversight of the installation contractor by the project's implementing agency or community entity. Finally, and most importantly, there must be sufficient preparation to organize a long-term service provider, either within the community or as an independent contractor, to maintain and repair the solar PV systems over time.

This section addresses the various activities that contribute to project sustainability, beginning with a discussion of the project design and implementation process, including project management and institutional preparation activities. Technical aspects of project implementation are mainly discussed in later sections of the module.

Project Identification and Analysis

Identifying where the solar PV project will be implemented is not complex in itself, but it implies execution of a larger plan of action, the purpose of which is to assist in providing electric service to a specific set of rural communities. The project implementing agency, whether it is an NGO, a faith-based community organization, a donor organization, or a government entity, must develop and evaluate a plan that includes prioritization of communities in specific geographic areas.

There are two principal goals associated with project identification for solar PV projects. First, it is important to take into consideration the means by which projects will be implemented, both during the project preparation and installation phase, as well as in the provision of service phase. Ideally, projects should be defined within a geographic area that can be managed by a local entity or a group of organized community members, such as a cooperative, consumer association, or some other community-based organization. The radius of project influence should thus not exceed the maximum distance the project implementation team can travel in a single workday. Road conditions, modes of transportation, and transportation costs are important factors to consider when evaluating a project's geographic scope.

The ultimate goal for any solar PV project should be sustainability of energy services over the useful life of the solar PV panels themselves.

Another important factor to consider is "minimal project size," or the minimum number of solar PV systems necessary to reach an economy of scale that allows a service provider to cover the cost of serving consumers. Service provider models vary rather radically in legal form, organizational format, and level of expertise. Many solar PV programs involve locally trained technicians, supported by a local administrator. In such cases, routine maintenance expenses are often quite low. While other models exist, NRECA's experience in this field has highlighted the critical importance of training and maintaining local technicians at the project site. Whether the service provider's institutional model is cooperative or private/for-profit, the costs of providing technical and administrative support to projects of this scale are unrealistic without locally available technicians. Regardless of the service delivery model that is employed, the development agency, electric cooperative, or NGO responsible for developing the project must consider the expected operating costs, together with the beneficiaries' ability to pay for service, when determining the required number of beneficiaries and the geographic scope of the project.

The final product of this planning phase involves defining where the project will be located, its geographic radius of influence, the project implementing agency's likely local counterpart agency (community organization, local political leadership, church group, etc.), and the target number of beneficiaries required for project long-term viability.

Many solar PV programs involve locally trained technicians, supported by a local administrator.

Community Organization

Community organization is one of the most critical activities contributing to long-term project sustainability. Community members, as the long-term owners or caretakers of service and assets, need to take ownership in the project itself. (Because many solar PV projects use lease or rental schemes for solar PV systems, the term "owners" is used in a figurative sense here.) Community input is essential for decision making, especially as it pertains to financial contributions to the project and the role and form of local system operation and maintenance entities. If community members do not feel sufficiently engaged in the decision-making process or feel their input is not welcome, significant difficulties in project execution and fee collection are likely to occur later.

There are many approaches to organizing communities and setting up organizations that can effectively interact with rural energy service project proponents and agencies. No form is ideal for all settings. Each social group has its own cultural, ethnic and social characteristics, all of which must be taken into account when making final decisions on which organizational structure to encourage and support. In all cases, there are existing institutional structures that have been used effectively by other development projects, so it is important to survey other development activities as indicators of which organizational and institutional structure might best fit the needs of the project under consideration.

Below are three general steps that have successfully helped establish well-functioning community organizations for solar PV projects:

1. Begin with focus group meetings with community leaders and elders. The purpose of these introductory meetings should be to make sure the community leadership favors supporting the project.

2. Conduct informative meetings with the whole community to explain the goals, objectives and work methods for the solar PV project under consideration. When defining the informational meetings, the team should be sensitive to the level of economic development present in the community, the level of education, and prevailing cultural biases. Seek to understand the development priorities and expectations of community members. Establish with community members that the project is open to all individuals within the community without discrimination.

3. Evaluate the need to form an organized legal entity (for example, a cooperative or consumer association or corporation), and evaluate it's the best form and legal options for the community. Note that while not all projects require legal entities, some work by organizing groups of communities under a common legal framework or umbrella.

If organizers determine the appropriateness of a formal entity, several additional steps are required. The project implementation agency should not assume that the community can successfully complete these steps without intermediation. Communities often require additional support.

Under a community development model often used by NRECA, the following steps are recommended to establish a formal community-based implementation, operations, and management entity, which ultimately acts as the de-facto energy service provider for the community.

1. Conduct a community assembly to explain the organizational process of the formal entity and to propose candidates for an interim board of advisors. This board of advisors will lead the decision-making effort during formation of the formal entity. As part of this process, the community assembly participants should vote to determine the form of their representative community entity.

2. The board of advisors works with the project implementation agency to develop articles of association or incorporation, an organizational plan, and policies and procedures regarding the entity's formal and legal registration.

3. Submit articles of association and other legally required documents to formally register the community entity. Convene a second community assembly to nominate and elect a Board of Directors. Use formal record-keeping to document all key events, decisions, and proceedings.

4. We strongly recommend that the Board of Directors specifically exclude local political leadership and clergy, if possible.

Once organized, the Board of Directors needs to form several working committees to begin to develop the policies, procedures, and organizational tasks for the entity. These committees may include, but will not be limited to an administrative committee, a governance committee, and a technical committee. The committees work with assistance from the project implementation agency to define the functions and scope of services of this newly formed entity, which has now evolved into the community energy service provider. In many cases, the project implementation agency may have sample policies and operating procedures ready for committee review. In this case, these committees participate in training sessions that help them better understand the functions required to effectively provide system maintenance and operating services.

Based upon the understanding of the functionalities that will be provided by the newly formed community energy service provider, the Board of Directors appoints a manager, technicians, and an administrator to oversee the functions of the new entity. All employees or consultants should be trained by the project implementation agency. The defining factor of a successfully operating community energy service provider is whether the entity is able to provide the required maintenance and operating services to assure that its members can continue to operate their solar PV systems over the useful life of the systems. This of course requires the ability to collect sufficient revenues to cover the cost of providing maintenance and repair services for the systems, and to attract technical assistance when necessary from the program implementing agency, or from another source of technical, administrative, or perhaps financial assistance.

The importance of collecting demographic data and data on willingness to pay cannot be overemphasized.

Demographic/Willingness to Pay Analysis

The importance of collecting demographic data and data on willingness to pay cannot be overemphasized. While many, if not all, solar PV projects receive substantial capital subsides, projects that have experienced long-term success have evaluated the capacity of beneficiaries to pay operating costs and have assured that these fees are collected on a routine basis.[2] Efficient bill collection allows the community energy service provider to replace batteries and charge controllers when necessary, and to perform routine and necessary maintenance, including refilling battery cells with distilled

[2] For more information on this process, see Module 6, *Consumer Willingness to Pay and Economic Benefit Analysis of Rural Electrification Projects.*

water, cleaning the PV panels to assure efficient operation, and troubleshooting outages when they occur.

A household energy survey should be conducted to collect and analyze data on individual household energy usage and costs within the project area. The household energy survey not only illustrates what community members are paying now for energy services, but it also provides information required to determine the appropriate size of the solar PV systems. Keep in mind that community members have varying incomes, and more affluent members may elect to pay for larger systems that provide more energy for lighting and other services.

Solar PV projects most often they require significant subsidies, provided either by a government entity, donor agency, or a non-governmental organization.

A household energy survey or demographic study can also be a vehicle to quantify local preferences, including the type of institution that is preferred, how involved community members want to be in project management and implementation, and what other services they would like energy systems to provide (water supply, energy for community centers, etc.). Programming and conducting these studies should therefore count as an integral part of the project implementation process.

Project Analysis and Feasibility

For most investments, measuring project feasibility is a straightforward process. A financial cash flow analysis uses estimations of capital and operating costs on the one hand, and projected revenues on the other. These are then used to determine net revenues over the expected project life. If the financial results exceed the investment group's required return on investment, the project is feasible. For infrastructure projects that yield economic and social benefits, with only marginal financial revenues, the process is somewhat different in that the costs and benefits of the project can be evaluated against the "target" economic rate of return. In such instances, projects that show economic rates of return that exceed the target economic rate of return are considered viable.

Solar PV projects fall into the latter category, given that most often they require significant subsidies, provided either by a government entity, donor agency, or a non-governmental organization. For solar PV projects financed by government agencies, the economic benefits are normally estimated based upon a regional or national economic evaluation study and quantified in terms of the value of the service per consumer served. This value then determines the maximum government or donor program subsidy provided to the project. If the project can be implemented for an amount not to exceed the maximum subsidy allowed, and if the government office or donor program agrees to provide the required funding, the project is considered viable.

In addition to the factors mentioned above are others that contribute to project sustainability. Projects should not only have to satisfy an economic benefit analysis, they must also demonstrate that the communities and implementing agencies have accomplished, at a minimum, the following:

- Established and organized a local entity that will collect tariffs, manage repairs and maintenance, and maintain communication with sources of technical assistance (a community energy service provider).
- Demonstrate that project beneficiaries have signed service agreements that describe the project implementation agency's responsibilities, identify a modest monthly service fee for system owners, and establish the terms and conditions for project operation.
- Show that administrators and technicians have received adequate training and understand the tasks required to maintain and operate the solar PV systems.
- Show that project beneficiaries have contributed to an initial capital fund (however modest in value) to allow the community energy service provider to pay initial operating costs, including administrator and technician salaries.

Projects that can accomplish these tasks and that demonstrate implementation costs less than or equal to the estimated economic value of the project, will be considered viable and will attract greater financing options.

Procurement Process

Procurement of materials and equipment requires an understanding of the products to be purchased, an understanding of the market from which the material will be purchased, and a well-defined, wisely designed procurement procedure. To assure that procurement results in obtaining high-quality materials at market-competitive prices, the process must be clear and transparent. Its policies must also encourage competition.

Given that most of the components for solar PV systems are made in relatively few countries, including China, Malaysia, India, and others, international bidding is likely necessary, resulting in substantial cost savings. Allowing and encouraging local vendors to participate in the bidding process is necessary and may enhance the project's ability to enforce warranties and guarantee a high quality provision of service.

While each organization is likely to use its own procurement procedure, many development institutions follow quite similar practices. A well-defined procurement process includes the following information components to facilitate qualified responses to a request for quote (RFQ) or request for proposal (RFP):

- *Characteristics of the project area.* These may include location, reference conditions (solar insolation levels, ambient conditions, rainfall data, etc.), community size, types of structures on which panels and system components will be mounted, etc.

- *Evaluation criteria.* This defines the basis for bids to be presented, and the qualities that will be examined to select the most attractive proposal.

- *Description of a bid response format.* These instructions describe how proposals should be presented, including the required data and product information, how to present prices, how to present transportation and insurance data, etc. To facilitate comparative evaluation of bids, it is usually best to include tables to be completed by each bidder to provide characteristics and prices of each item included in the bid.

- *System and component specifications.* This section provides a detailed set of specifications of each system component, including references for equivalent products.

- *Standard contract and payment terms.* While a standard contract is not always included, it may facilitate completion of the procurement process. Advise bidders here of the preferred mode of payment.

To assure that procurement results in obtaining high-quality materials at market-competitive prices, the process must be clear and transparent.

Project Execution

Once materials have been purchased and an installation contractor has been hired (if the bid does not include installation services), the project is ready for installation. Provide installation oversight by hiring and training inspection technicians to ensure that the solar PV systems are properly installed, that the users are trained to use and care for the solar PV systems, and that all components are functioning properly. Ideally, the community technicians responsible for maintenance and repair of the PV systems participate in or directly manage this process, but in any case, be sure to train the technicians responsible for the inspection of newly installed systems.

During the installation phase, also provide further detailed training to the administrator and technicians charged with managing the post-installation services for the project beneficiaries. Multiple training opportunities, even if they are repetitious in nature, help bring about project success.

Should any component failures be noted during the installation phase, a claim should be made with the vendor to replace the defective products, or to otherwise repair them against the product's warranty. As far as possible, test all systems and components to make sure they are functioning according to product specifications.

Service Provision: Project Operation and Sustainability

Successful and sustainable solar PV projects depend on the involvement of all players.

After installation of the solar PV systems, a community energy service provider typically assumes responsibility for all maintenance and repair functions. Given that these entities are largely informal in outlook and practice, a proactive program of monitoring and assistance is necessary. Many projects, and perhaps most projects, proceed on the assumption that consumers will seek and be able to find service providers for routine maintenance and repairs. In some cases, the community may contract with a private firm to carry out this responsibility. However, NRECA's experience has shown that often such service providers are not available. In addition, this option imposes greater costs on the community and the project. Ongoing technical assistance and training to strengthen administrator and technician capacities are essential for long-term project success.

Among many other aids, community energy service providers (or whichever organization is formed to manage the project after implementation) require basic skills to account for and manage financial resources, assist in record keeping, perform routine maintenance activities, and to trouble-shoot technical difficulties as they arise. For training and reference purposes, we recommend that the project implementing agency develop a simple, illustrated instruction book to provide guidance for service technicians. The reference book should emphasize information included in training sessions, provide very practical and easy-to-follow instructions, and provide a list of all tools and materials required for each task described.

The importance of providing periodic training and technical support to the community energy service provider personnel over time cannot be overemphasized. Once solar PV systems are installed, especially for projects in remote areas, it is unrealistic to assume that vendors will send service technicians to diagnose and repair these systems. Local technical support will be essential, so continued training and support to the local personnel serve as the key to long-term sustainability.

Project implementers should therefore include local technicians during the various installation activities of the project, so they can learn on the job and provide basic troubleshooting services to the community energy service provider. Training backup local technicians (one or more, depending on the project size) as well allows for more continuous coverage of maintenance and other issues and reduces overreliance on one individual.

Successful and sustainable solar PV projects depend on the involvement of all players. A community that is knowledgeable and well trained on the benefits, complexities and potential problems of their solar PV systems will ultimately pave the way for project sustainability. Well-guided and appropriate technical calculations and decisions are important. Nevertheless, a well-organized community with several trained technicians will be able to overcome many of the limitations imposed by even the best-designed systems.

SOLAR PV SYSTEM DESIGN PARAMETERS

The first task in designing a stand-alone solar PV system is to evaluate energy consumption of the target community. The energy consumption of prospective households determines the size and characteristics of the solar PV system that satisfies their energy requirements. Dimensioning a solar PV system is a relatively simple process that can be accomplished in several steps. Standardization within solar PV systems is relatively common today, after over 20 years of experience in remote applications. The decision-making process actually has less to do with engineering design than it has to do with matching system component capacities with consumers' ability and willingness to pay for the service. This means that dimensioning solar PV systems is first and foremost a function of understanding energy requirements, and dimensioning the panel, the battery, and ancillary components to meet the energy needs of the consumer. If consumers desire lower-cost energy service, the system capacity can be correspondingly reduced.

Therefore, surveying consumers' needs, preferences, and economic capacity is important. Data that is required to appropriately size a solar PV system for a household include:

- Historic energy consumption patterns, by type of service, use and energy supply (examples: lighting via candles or kerosene lamps, heating via firewood, cooking via charcoal or propane stoves, etc)
- Ability and willingness to pay for energy service[3]
- Potential to use electricity to increase income generation capacity through increased production[4]
- Confirmation of solar energy radiation
- Capacity for local technicians to manage installation and maintenance requirements
- Availability of locally procured system replacement parts

[3]For more information on this process, see Module 6: *Consumer Willingness to Pay and Economic Benefit Analysis of Rural Electrification Projects.*
[4]For more information, see Module 9: *Productive Uses of Electricity.*

Energy Balance

As mentioned above, the most critical factor in determining system capacity and design configuration is the evaluation of community energy requirements, to determine whether the calculated energy demand can be satisfied with solar photovoltaic energy or other renewable resources. If a household's energy requirements are limited to lighting and other low-energy consumptive uses, such as television and radio, solar PV systems can be an ideal solution. Dimensioning the system becomes a simple exercise of selecting a solar PV panel size, determining the desired number of days of autonomy (days without sunlight), and selecting components accordingly. Standard design methodology requires that the system engineer base the panel and battery size on the solar insolation level for the month of minimum radiation, together with expected consumption during this time of year. (Insolation is a measure of solar radiation energy received on a given surface area in a given time.)

The first task in designing a stand-alone solar PV system is to evaluate energy consumption of the target community.

Estimating the Energy Supply

Approximate values for solar insolation are readily available for most areas throughout the world. Solar radiation maps are widely available from many institutions via internet databases. More precise levels of radiation can be acquired through national or international meteorological databases, such as the U.S. National Oceanic and Atmospheric Administration (NOAA), National Climatic Data Center.

National atmospheric databases normally contain decades of weather data, with data most often presented for discrete years, and in the form of statistical averages. In the Dominican Republic the agency that collects, processes, and distributes this data is the National Meteorology Institute and the Institute for Hydraulic Resources. In Guatemala, the institute responsible for data collection and dissemination is the Institute for Seismology, Volcanology, and Meteorology.

Three complementary sources indicators provide information that can be useful in determining whether there is sufficient solar insolation for the use of solar PV systems.

Vegetation

Certain plants are indicators of the intensity of solar insolation due to their preference for environments with high degrees of sunlight. For example, many species of the cactaceae family (of which the cactus is a member, native to the Americas) and the leguminosae family (also known as the fabacaea, commonly known as the legume or bean family) prefer abundant sunlight. Consider also that communities where vegetation grows lower to the ground are preferable for solar PV systems because such vegetation naturally tends to produce less shade. Keep in mind that the more shaded an area is, with vegetation or otherwise, the less solar insolation it has, and therefore the less useful a solar PV system becomes.

National atmospheric databases normally contain decades of weather data, with data most often presented for discrete years, and in the form of statistical averages.

Topography

Topography is not critical to dimensioning or implementing solar PV systems for rural electrification, except for areas with pronounced topographic changes, which can cause shading effects, depending on the location and orientation of the community within the area. Topography also can be useful information for estimating difficulties in deployment or installation of the program activities. Topographic data are commonly available in many countries through national cartographic institutes, and may also be available through international agencies, such as the United Nations Development Program (UNDP).

Climate

Weather data, including prolonged periods of cloud cover, are extremely important for final project design. Because national data sets are often not based on data derived from weather stations, data provided by national weather or climate centers can often lack precision, especially for estimating battery capacity (days of system autonomy).

It is always useful to consult with farmers and technicians in the area, or those tradesmen and business people whose activities depend upon the frequency and/or duration of rain. These local sources can provide information concerning cloudiness, relative humidity, fog, wind, and other elements that can affect the efficacy of a solar PV system's operation.

Estimating Energy Demand

Estimating energy demand involves estimating average daily and monthly energy consumption for the target project population. The most common tool used to determine energy consumption is a household energy survey. As was previously mentioned, this tool collects basic demographic information from randomly selected households, statistically evaluates consumption trends, and determines consumer ability to pay for energy service (electric and non-electric). Some of the most important data collected in a household energy survey include the following:

- Fuels, appliances, and fuel consumption used for lighting purposes. The analyst must attempt to tabulate all forms of lighting that may be employed, including candles, flashlights, kerosene lamps, gas lamps, and electric lights. The survey ascertains fuel consumption for each individual technology, together with prices and average monthly cost.

- Fuels, appliances, and fuel consumption used for cooking. If more than one fuel is used for cooking (a combination of wood and charcoal for example), quantities and prices are estimated for each. Liquified petroleum gas (LPG) and kerosene may also be used in combination with other fuels.

- Fuels, appliances, and fuel consumption for other uses of electricity. This could include either a car battery used for powering larger portable radios, or small gasoline or diesel generators to power televisions or refrigerators. LPG used to fuel any other appliance must also be listed. A key example is an LPG-powered refrigerator. The analyst must note the name-plate capacity (in watts) of each appliance, its respective generating unit (e.g. a battery or a generator), the estimated average use per day or week, and any comments from the surveyed household on possible changes in consumption. For personal generators, note the type of fuel used, the daily/weekly/monthly consumption of fuel and its associated cost, its name-plate capacity (in kVA and kW). Also list the appliances powered by the generator. For larger batteries, note the capacity of the battery(ies) used, the daily/weekly/duration of their use (and for what appliance), as well as the cost and frequency of recharging.

- For households surveyed that have access to electric service, develop a table of the type and number of electric appliances. These might include a radio, television, refrigerator, fans, etc. This table would include the name plate capacity (in watts) of each appliance, the estimated average use per day or week, and any comments from the surveyed household on possible changes in consumption. Ask for past electric service bills (typically three are sufficient), keeping in mind that energy consumption varies depending on the seasons.

From the survey forms, tabulate the data into a database, then statistically analyze the data to provide energy consumption estimates for the project area, as well as estimates for the average individual consumer. The analyzed dataset will also yield willingness and ability to pay estimates, which in turn becomes input for evaluating service provider models for the project area.[5]

[5]For more detailed information on willingness to pay, see Module 6, *Consumer Willingness to Pay and Economic Benefit Analysis of Rural Electrification Projects*.

System Components

The principal components of a solar PV system include the solar PV panel, the battery, the charge controller, lamps, outlets, and connecting/mounting hardware. The component capacities are dimensioned to satisfy the consumer demand that was determined from the household energy survey.

TECHNICAL SPECIFICATIONS FOR STAND-ALONE SOLAR PV SYSTEMS

The principal components of a solar PV system include the solar PV panel, the battery, the charge controller, lamps, outlets, and connecting/mounting hardware.

Presented below are the suggested minimum specifications for the principal components of solar PV systems for rural electrification applications. These specifications promote longevity of service and reliable operation of the solar PV system.

Photovoltaic Module

The solar photovoltaic module consists of both the module and a connection box terminal. The photovoltaic cells can employ mono-crystalline, polycrystalline, or non-crystalline/amorphous silicon. Mono-crystalline, or single crystalline, silicone modules are primarily used in space related PV applications due to their high efficiency; however this is matched by their high manufacturing costs. In general, polycrystalline modules are most often preferred for rural and urban PV systems. As compared with non-crystal/amorphous crystalline modules, polycrystalline modules have a higher stability of the substrate, and therefore relatively stable electric output over the useful life of the models. Amorphous modules are cheap but inefficient, while single crystalline silicone modules are more efficient but costly.

The module frame, which protects the solar panel and connects it to the outside of the house or a pole, should be aluminum and of sufficient thickness to withstand expected wind stress for the project area. The peak nominal power value for each module must be clearly indicated on the module itself. The most important specification of panel output is the rated peak watts (Wp) under maximum solar insolation (1 kW-square meter).

All solar PV modules, whether amorphous or polycrystalline, must have a UL (Underwriter Laboratory) certification and recent applicable panel quality tests. The panel quality test should be certified by the International Electro-technical Commission (IEC), the U.S. Jet Propulsion Laboratory or the ISPRA (Community Research Center in Italy).

NRECA recommends open-cell, flooded lead-antimony and deep-cycle type batteries for solar PV systems for rural electrification applications.

Warranty information for the module must be clearly specified on the warranty certificates provided with the product. The manufacturer warranty must cover defects in fabrication and/or assembly. All panels should be warranted to produce no less than 90% of nominal power during the first 10 years of operation.

In addition to warranty information, manufacturers and vendors should provide current-voltage curves that illustrate the module output under standard photovoltaic cell testing conditions. Standard test conditions are at a solar radiation intensity of 1000 W/m2 (one standard sun), with a cell temperature of 25°C.

Battery

NRECA recommends open-cell, flooded lead-antimony and deep-cycle type batteries for solar PV systems for rural electrification applications. Although in many developing countries new or used 12-volt car batteries are often used with solar PV systems because they are cheaper and easier to find and replace, NRECA does not recommend them due to the short life expectancy of the former and the discharge characteristics of the latter.

Manufacturers and/or vendors should present performance data and physical characteristics of the batteries supplied. The data should include a description of the technical and mechanical characteristics of the battery; a charge and discharge curve for C/20 and C/8 rates of discharge; estimated battery life cycles at 50% depth of discharge; and the length and terms of the warranty. (C/20 refers to a current draw at which the battery will become fully discharged within 20 hours; similarly, C/8 is the rate of discharge corresponding to full discharge within 8 hours.)

Charge Controller

The charge controller, or regulator, regulates charge and discharge current from the batteries, besides connecting the solar PV panel and appliance or lighting loads to the battery. The charge controller protects the battery from over-charging and excess discharge by connecting the battery to the solar array when the voltage level drops below a prescribed level, and disconnecting the battery when the voltage reaches a maximum level. The connect and disconnect set points are distinct for each battery type, so it is very important to make sure that regulators are specified to work in tandem with a specific battery. Charge regulators are rated by maximum current-carrying capacity that is normally specified as 125-150% of the maximum expected load for the solar PV system.

Modern regulators are controlled by microprocessors and are pre-programmed to provide temperature compensation to regulate the charging algorithm to adjust itself with changing ambient conditions. Modern regulators also employ a charging pattern known as pulse width modulation to make the battery charging cycle more efficient. The following characteristics should be specified when purchasing charge regulators:

- The charge controller must protect against:
  - Short circuits in the charge terminal
  - Transient waves of voltage induced by atmospheric discharges (lightning)

- Polarity reversal in the module's terminal

- Temperature compensation should adjust the charging current to the battery against varying ambient conditions.

- Charge algorithm should employ Pulse Width Modulation (PWM).

- Set points for disconnection and reconnection of the battery charging cycle (for lead antimony batteries) should be as follows:

  - High voltage disconnection (HVD) at 14.2 V +/- 0.2V

  - Low voltage disconnection (LVD) at 11.5V +/- 0.2V

  - Low voltage reconnection (LVR) at 12.5V +/- 0.2V

- The regulator should have easy-to-read indicators illustrating the battery's state of charge, including a light that shows when the battery is fully charged and a series of lights to indicate the level of charge.

- The regulator must have a frame resistant to rust, with an encapsulated IP index of 5.4 (resistant to dust and water spills).

Lighting and Lamps

Normally, stand-alone solar PV systems produce very little electric energy in comparison with conventional fossil-fuel based portable power systems. For this reason, energy conversion devices, including lamps, must employ the most efficient technology available. Lamps used in conjunction with solar PV systems should be fluorescent-type tubes or compact fluorescent bulbs.

A typical fluorescent lamp is composed of the tube or bulb, electronic ballast, a frame, and mounting accessories. Compact fluorescent bulbs integrate the bulb and ballast in a single, enclosed bulb that can be fitted into a standard light fixture, either overhead or mounted in a table lamp. These bulbs are very convenient, and with mass production, they are becoming more competitively priced with tube-type fluorescent lamps. NRECA recommends the following lamp characteristics:

- Nominal voltage of operation should be 12 V DC.

- Recommended nominal capacity can vary from 7 to 20W, depending upon illumination requirements.

- To avoid the temptation to use incandescent bulbs in conjunction with solar PV systems, we recommend against use of the common screw or the bayonet-type inserts. We recommend lamps that require direct connection via a wiring fixture.

- Use lamps that are protected against polarity reversal.

- The color index of the bulbs (CCT) should exceed 3000K.

- The frame of the lamp should include a white reflector to maximize illumination. Use of diffusers is discouraged.

- Protect the lamps against dust and insects by mounting them in sealed enclosures.

- Purchase each lamp in conjunction with the appropriate ceiling or wall mounting fixture and hardware.

Lamps used in conjunction with solar PV systems should be fluorescent-type tubes or compact fluorescent bulbs.

DIMENSIONING SOLAR PV SYSTEM COMPONENTS

Solar PV systems are dimensioned in distinct sizes, based upon the daily energy consumption determined through the household energy survey, the number of days of autonomy required, and the panel capacity, measured in peak watts (Wp). Since panel and battery manufacturers produce products with distinct characteristics, systems are dimensioned to satisfy a specific operating range of energy consumption in a way that is consistent with the modules' operating parameters.

While system efficiency and performance are important characteristics, durability and reliability are higher priorities.

While system efficiency and performance are important characteristics, durability and reliability are higher priorities. With this in mind, adhere to the following principles should be adhered to when defining system characteristics:

- *Simplicity.* Commonly, more complex systems require a higher degree of maintenance and technical support. Avoid system complexity, unless there are overriding reasons in support of it.
- *Equipment performance data.* Solar PV panels should include third party performance certificates. Batteries, charge controllers, and lamp products should conform to international safety and performance specifications.
- *Efficiency.* Products with demonstratively higher performance efficiency will result in financial savings and greater net energy supply. However, higher efficiency products must be balanced against the cost of maintaining advanced electronic components.

Dimensioning Solar PV Panels

Each step of the design process requires a specific procedure to ensure that the energy generated and stored in the battery will meet the energy needs of the target beneficiaries. For solar PV systems, normally the energy service provided will be sufficient for lighting purposes for powering a small television set and/or a radio.

Most stand-alone solar PV home systems are designed around a specific lighting load, such as two or three lamps, rated at 11, 15, or 18 watts. In the calculations below, we assume that the solar PV system will provide electricity for three 11-watt lamps to be used for three hours per night, as well as a small television set to be used for three hours per day. Other combinations of lights and television usage could be used by the design engineer to meet user preferences.

The first step in this process is to calculate the specific system load, or the total amount of energy drawn by the electrical devices connected to the PV system. Calculating the system's load will allows the system designer to properly dimension the panels, batteries, and other components, as well as estimate the project's cost. Estimating loads, especially in non-electrified areas, can be at times difficult but it is normally a relatively simple process.

Design the system for the worst-case scenario while at the same time remembering to account for consumers' ability and willingness to pay for the system. In some cases, a consumer's limited ability to pay for the service or system affects the final design of the system, usually limiting the system's loads to keep equipment capital costs as low as possible.

In most rural electrification projects using renewable or isolated generation systems, the designer must first determine whether the system will use direct current (DC) or alternating current (AC). Most solar PV systems use a DC current electrical wiring system, especially in isolated rural areas. DC systems allow for easier storage of electrical energy (in batteries), are less sophisticated, and cost less overall. AC systems, on the other hand, are normally used when energy must be transmitted or distributed over larger distances, to use specific household or consumer appliances, for connection to the electric grid, and/or for convenience.[6] Therefore, the example to follow, like most solar PV projects, uses a DC system. The lighting apparatus, batteries and

[6]Inversin, Allen R. *Micro-hydropower Sourcebook: A Practical Guide to Design and Implementation in Developing Countries*. London: ITDG Publishing, 1986.

appliances will also be designed and selected according to a DC system.

Assuming the selection of a DC solar PV system, the next step requires the designer to determine the operating voltage of the system. Most DC systems run in increments of 12 volts (V) from 12 – 48 V DC. For DC systems, this selection is made based upon the requirements of the largest load. A 12 V DC system can be used in most solar PV systems smaller than 1 kilowatt.[7] As an aid to this process, the designer may calculate the total system power demand, in watts or kilowatts. Rural solar PV projects typically are 12 V DC systems.

Next, the designer must determine the type, capacity, quantity, and usage of the power load even though the load might not yet exist. Therefore, the designer must work with the community to determine what loads are appropriate, based upon the project's cost. An example of this information is presented below in Tables 1 and 2. In our example, the system load characteristics are the following:

- Three 11-watt lamps, used for 3 hours per day
- One 20-watt television, used for 3 hours per day

Note that in the example cited above, all three lamps are identical (in type and capacity). If different wattage lamps are used, the designer must calculate separate power demands for each.

The next step is to multiply watts (W) times hours of use and quantity, for each identical load to arrive at daily consumption in watt-hours. Using the lamps example, 3 (quantity) multiplied by 11 (watts capacity) multiplied by 3 (hours of daily use), equates to 99 watt-hours daily consumption. Using the same formula, we calculate 60 watt-hours as the total daily consumption of the TV.

The designer then multiplies the daily watt-hours load for each appliance by an efficiency factor (which can be estimated at 1.5 for most small-scale stand-alone solar PV systems) to obtain daily adjusted watt-hours use. The efficiency factor accounts for several factors, including wiring and interconnection losses, all system efficiencies, and battery charge and discharge cycles.[8] Adding the daily adjusted watt-hours usages for each appliance yields the total adjusted watt-hours use for the system. This figure is used to dimension the solar PV array. Table 1 shows a calculation for the above-mentioned process, in which a total of 238.5 adjusted watt-hours load was calculated for the system as a whole.

The designer must note whether appliance use will vary greatly depending on the seasons or months of the year. System load calculations may be required for each different season (summer vs. winter, for example) depending on the size of the

The designer must determine the type, capacity, quantity, and usage of the power load even though the load might not yet exist.

[7]*Sandia National Laboratories. Stand-Alone Photovoltaic Systems a Handbook of Recommended Design Practices*. NY: Ntis, 1995.

[8]Sandia National Laboratories. "Recommended Design Practices." Photovoltaics Main Page. 8 Jan. 2009 <http://photovoltaics.sandia.gov/docs/Recommended%20Design%20Practices.htm>.

Table 1. Example of calculating system loads

Appliance	Quantity		Watt Capacity (per unit) (W)		Usage (hours per day)		Daily Watt-hours load		Efficiency (decimal)		Daily Adjusted Watt-hour load	Operating Voltage (DC	Power Conversion Efficiency	Daily Amp-hour load (AH/Day)
Lamps	3	x	11	x	3	=	99	x	1.5	=	148.5	12	1.0	8.25
TV	1	x	20	x	3	=	60	x	1.5	=	90.0	12	1.0	5.0
TOTAL							159				238.5	12	1.0	13.3

system. In most small stand-alone PV systems, when electricity is used to power lighting and an entertainment source only, this dual calculation is not necessary. Nevertheless, the designer should still design a system for the worst-case scenario, depending on the cost.

After calculating the daily load on the system, the designer next dimensions the solar array, which consists of a number of solar modules connected together in series or parallel. This step calculates the number of modules required. It actually involves three tasks that must be accomplished but in no particular order. The most important of these tasks for the designer is calculating the average hours of sunlight per day available in the area. For areas where solar resource data is available, this variable is usually measured in energy per surface area per day (or $kWh/m^2/day$). Keep in mind that this variable changes with the seasons as well as with the community's distance from the. The farther away the community is from the equator, the more this variable fluctuates during the year. Another important variable in this calculation is the relative cloudiness of the community. Since macro-level national weather data often lacks the level of precision required, it is important to discuss climate patterns (rainy season, humidity, etc.) with local community members. On average, most sites allow for 4-5 hours of sunlight per day.

As part of calculating the hours of sunlight per day, designers need to determine the angle of tilt of the solar PV array. For stand-alone solar PV systems, the angle of tilt usually ranges from -15° to +15°. Larger systems do at times employ bi-directional tilting and tracking, but these concepts are highly uncommon in small-scale solar PV systems and therefore are not discussed in this module. The angle of tilt selected is a variable of the community's latitudinal position on the globe. Designers should consult other practitioners in the country, or the relevant government agency, to ascertain the proper degree of tilt for the latitude of a certain community.

If no hours of daily sunlight data are available for a particular site, the analyst must conduct several field tests to obtain the data. The system designer must manually calculate this variable by measuring the hours of peak sunlight – the number of hours per day during which solar irradiance averages 1000 W / m^2. Keep in mind that the hours of sunlight may change significantly depending on the community's latitude and the season.

The example below uses the estimate of 4.5 hours of sunlight being available per day on average. Designers based this on national climatic data as well as consultations with community members.

Next, to dimension the solar PV array, the designer divides the daily adjusted watt-hour load by the daily average hours of sunlight. In Table 2, this calculation results in a required array wattage of 53 watts.

Following this, the designer and project team must survey the market (local, national, and perhaps international) for solar PV modules that would best fit their needs. This research can also be conducted much earlier in the design phase. The selection of a PV module depends on a variety

Table 2. Example of solar PV array dimensioning

Daily Adjusted Watt-hour use		Daily hours of sunlight		Required Array Wattage (W)		Solar Module Wattage Selected (W)	Quantity Desired
238.5	/	4.5	=	53.0		60	1

of factors, of which critical importance should be placed on quality, market availability, local availability of replacement parts and technical support, valid warranties on modules and parts, as well as UL (Underwriter Laboratory) certification and recent applicable panel quality tests.

In selecting a PV module, the team must look at both electrical capacities and cost. For example, in Table 2, a 53 watt array is needed. However, the designer will probably not find a specific solar PV module rated for 53 watts. Always round up, not down. In our example, the module selected was rated for 60 watts, resulting in only one module being required to fulfill the system's load demands. If a 60-watt panel were not available, the design team would have to consider other options, including using two smaller wattage modules or using a single module of larger watt capacity.

In most developing country solar PV markets, the variables of cost and quality play a key role. Often the lowest-quality modules are the cheapest, and therefore consumers are often drawn to them as the better option. Poor-quality products are much more expensive in the long-term, due to the high and reoccurring cost of maintenance or replacement.

Dimensioning the Batteries

Batteries are the most problematic component of a solar PV system, as well as the component most likely to fail if improperly sized to meet the loading conditions imposed by its users. Lead acid batteries last much longer if they are minimally discharged to no more than 20% of their rated capacity on a daily basis, while deep discharge batteries can be drawn down to 80% of their capacity, with only 20% of the charge remaining. However, they last longer if they are operated in so-called "float mode," at the upper 20% of their total capacity.

In evaluating battery options, it is important to dimension battery size by five times the daily expected energy requirement, if possible. This requires that the design engineer evaluate the daily energy demand and the number of days of autonomy that are desired, then assume a low charge-discharge efficiency for the battery cycle. The round-trip (charge-discharge) efficiency is normally approximated at 50%. This means that only 50% of the energy that goes into the battery is ultimately available for use to serve the load.

First, the analyst must calculate a daily adjusted watt-hour load on the battery by assuming a total round-trip battery efficiency of 50%. Therefore, the daily watt-hour load is multiplied by 1.5. In the sample calculation in Table 3, this gives a daily adjusted watt-hour load of 238.5. The adjusted daily load is then multiplied by 5, so that the battery or batteries ensure a 20% daily drawdown, giving a battery design load of 1192.5 watt-hours. The daily discharge factor prevents the batteries from being deep-cycled daily (drawn down to the lower 20% of their capacity), leaving this duty for only occasional necessity. Then to calculate the required battery amp-hours, the designer divides the battery design load by the system's nominal voltage (12 Volts DC in this case), giving a required battery amp-hours figure of 99.4 AH/day.

Batteries are the most problematic component of a solar PV system, as well as the component most likely to fail if improperly sized to meet the loading conditions imposed by its users.

Table 3. Sample battery sizing calculation

Daily Watt-hour load		Battery Efficiency Factor		Daily Adjusted Watt-hour load		Daily Discharge Factor (for daily discharge of 20%)		Battery Design Load (watt-hour)		Nominal System Voltage (V)		Required Battery Amp-hours (AH)		Amp-hours of Battery Selected (AH)	Number of Batteries Required
159	x	1.5	=	238.5	x	5	=	1192.5	/	12	=	99.375		105	1

Finally, the project team must again survey the market for available and appropriate batteries. The selection of a battery greatly depends on market availability and price. Again, remember that the listed daily amp-hours of the battery should be more that what is required by the system's loads and conditions. Dividing the amp-hours required, by the amp-hours listed on the battery selected results in a figure for the number of batteries needed. Always select batteries of high quality. While costs should be kept in mind, choosing a higher quality product can result in cost savings by avoiding expensive repairs, having to buy replacement parts, or even needing to replace the battery. As a general rule of thumb for PV systems, the bigger and heavier the battery available, the better.

Charge controllers must also match the characteristics of the battery that is selected for the solar PV system.

When selecting a battery, also consider the availability of compatible charge controllers. A discussion of charge controllers follows below. Avoid automobile batteries if possible. Automobile batteries quickly become useless when integrated into a solar PV system. Solar PV systems charge their complementary batteries slowly over long time periods, while automobile batteries are designed to be quickly recharged, and they produce only a high current in a short time span. Finally, keep in mind that even PV batteries do not last as long as the useful life of the PV array (20-25 years in most cases). Commonly, deep-cycle batteries have a useful life of 5-10 years.

Balance of System Components

The following practical criteria must be considered in the dimensioning of the balance of system components.

Charge Controller

Select the charge controller based on the expected peak load amp capacity of the solar PV system, as well as the characteristics of the battery. Designers often select charge controllers by evaluating the expected peak current and multiplying this current by a safety factor of 1.25-1.5.

Charge controllers must also match the characteristics of the battery that is selected for the solar PV system. Lead antimony batteries have distinct characteristics from lead calcium batteries; the high voltage disconnect and low voltage reconnect points are different from one another. Therefore, the type of battery (lead acid versus lead antimony) should be evaluated prior to selection of the charge controller. NRECA recommends the use of open-cell, flooded lead-antimony and deep-cycle type batteries for solar PV systems in rural electrification applications.

Lighting (Lamps)

Lamps are available in a variety of sizes to suit many different applications. Lamp rating normally goes by the luminosity that is required for the room to be lit. Small bedrooms may require compact fluorescent lamps of 7-9 watts, while larger dining and living areas may require multiple lamps with a capacity of 18-20 watts.

In addition to determining the size of the lamps used, consider costs and market availability. Avoid lamps that must be specially imported as they are not practical in the longer term. Incandescent lamps are also not suitable for solar PV systems. In most cases, compact fluorescent light bulbs (CFLs) are used in place of incandescents due to their higher efficiency. Again, pay close attention to the quality of the CFL or lamp selected. Where less light may be needed, light-emitting diode (LED) lamps are a possibility.

Wiring

In selecting internal wiring (also known as conductor) size, the goal is to minimize energy loss and voltage drop. Voltage drop is an important for conductor size if loads are located far away from the battery and voltage regulator. Given that solar PV systems normally operate at 12-24 volts DC, line loss and voltage drop can be significant unless caution is used in selecting conductor size.

In all cases, we recommend applying the national electric code when selecting wire size for reasons of safety and system performance. If there is no published national electric code, NRECA recommends use of the National Electric Code of the U.S.

Conductors selected should meet the worst-case scenario conditions of the system and its environment. Consider also whether the conductor will be installed in direct sunlight, buried underground, or both. In addition, analyze the ambient and operating temperature of the conductor. It is often best to work with the solar PV array vendor to select the most appropriate conductor type for the system, keeping in mind its design and layout.

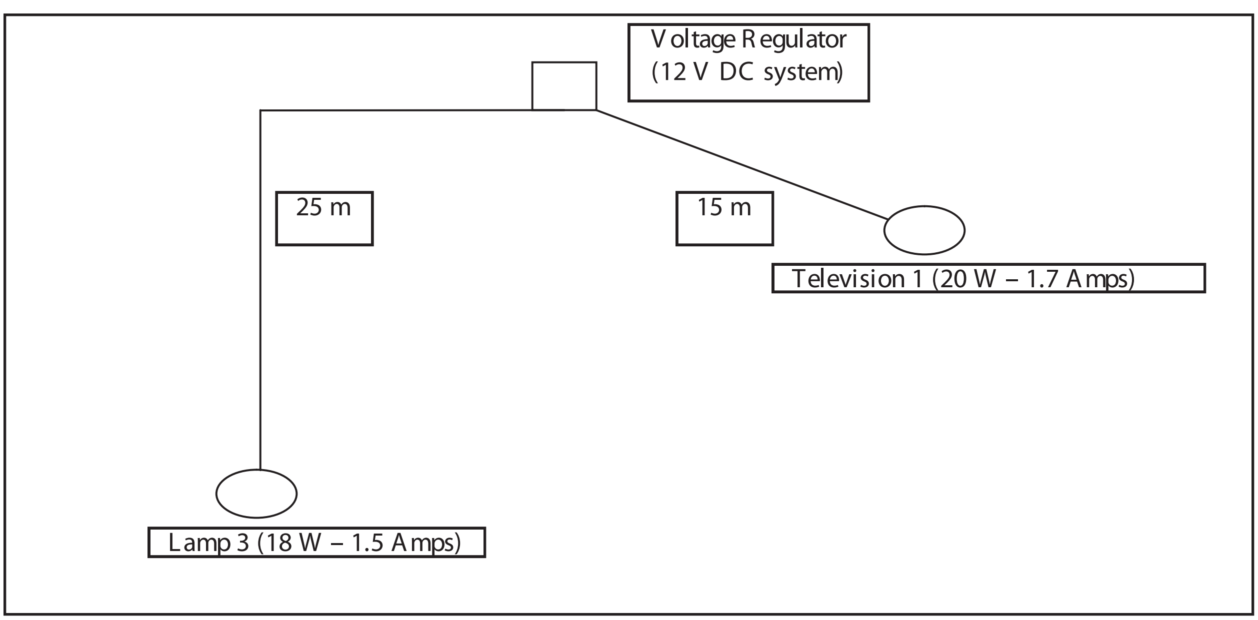
Select conductor caliber/size to result in a voltage drop of less than 3% for all wire connected to the voltage regulator. To calculate voltage drop, the system designer must employ a wiring diagram that clearly shows the location of loads, the maximum current of each load, and the distance from the loads to the voltage regulator. Using the known resistance of the conductor (derived using the American Wire Gauge scale – AWG, also known as the Brown & Sharpe wire gauge scale), the voltage drop can be calculated using Ohm's law.

For example, consider a solar home system that has two circuits, one for a single 18 watt lamp, and the second connecting to a 20 watt television. In the first circuit, the lamp is 25 meters from the voltage regulator, and in the second circuit, the television is 15 meters from the regulator. Using a wiring table, the designer can select the appropriate conductor for the solar home system, using a single conductor for both circuits by the following method. First, the designer must diagram the proposed wiring scheme, noting the location of the loads with respect to the source (or voltage regulator in this case), distance, watt power of each load, and maximum current. A simple wiring diagram for the above mentioned system can be seen in Figure 1.

After the designer has drawn the wiring diagram, he or she can proceed with calculating the voltage drop for each load. To do this, first the analyst must select a conductor gauge, which in essence is its diameter. The selection of which conductor gauge to employ is a function of the voltage drop across the whole system as well as cost. The larger the diameter of the wire, the lower the voltage drop will be, but the higher the cost. Therefore, the designer must be careful to balance technical design with cost.

Conductors selected should meet the worst-case scenario conditions of the system and its environment.

Figure 1. Sample wiring diagram



With these dueling criteria in mind, the analyst selects the conductor with the smallest diameter, which results in a voltage drop of less than 3%. For our case, let us assume selection of a 14 AWG gauge wire. Using the wiring table, we can deduce that this wire has a resistance of 0.008 ohms per meter. Then, multiply the wire lengths for both loads by this per meter resistance to obtain the resistance from the source to the load, R. After calculating the resistance in the wire, we can calculate the voltage drop for each load using Ohm's law, I = V/R (equivalent to V= IR), or voltage equals current multiplied by resistance. Therefore, the voltage drop across that section of wire is the resistance multiplied by the current drawn by the load. This calculation yields the voltage drop within the circuit. Taking this voltage drop as a percentage of the circuit voltage results in the percentage voltage drop.

Table 4 presents a calculation for voltage drop using different conductor AWG gauges. The most applicable conductor gauge is highlighted because it allows for a voltage drop of less than 3% for all circuits while keeping conductor diameter to its lowest value. The 14 AWG gauge conductor is therefore most appropriate for this system.

For further information on voltage drop, refer to any credible electrical engineering text.

Table 4. Voltage drop calculation chart

AWG gauge	Conductor Diameter (mm)	R per km	R per m	R x 15 m	R x 25 m	VDtv	VDlamp	VDtv (%)	VDlamp (%)
1	7.348	0.406	0.000	0.006	0.010	0.010	0.015	0.09%	0.13%
2	6.543	0.513	0.001	0.008	0.013	0.013	0.019	0.11%	0.16%
3	5.827	0.646	0.001	0.010	0.016	0.016	0.024	0.14%	0.20%
4	5.189	0.815	0.001	0.012	0.020	0.021	0.031	0.17%	0.25%
5	4.620	1.028	0.001	0.015	0.026	0.026	0.039	0.22%	0.32%
6	4.115	1.296	0.001	0.019	0.032	0.033	0.049	0.28%	0.40%
7	3.665	1.634	0.002	0.025	0.041	0.042	0.061	0.35%	0.51%
8	3.264	2.060	0.002	0.031	0.052	0.053	0.077	0.44%	0.64%
9	2.906	2.598	0.003	0.039	0.065	0.066	0.097	0.55%	0.81%
10	2.588	3.276	0.003	0.049	0.082	0.084	0.123	0.70%	1.02%
11	2.304	4.133	0.004	0.062	0.103	0.105	0.155	0.88%	1.29%
12	2.052	5.209	0.005	0.078	0.130	0.133	0.195	1.11%	1.63%
13	1.829	6.570	0.007	0.099	0.164	0.168	0.246	1.40%	2.05%
14	1.628	8.282	0.008	0.124	0.207	0.211	0.311	1.76%	2.59%
15	1.450	10.444	0.010	0.157	0.261	0.266	0.392	2.22%	3.26%
16	1.290	13.172	0.013	0.198	0.329	0.336	0.494	2.80%	4.12%
17	1.151	16.610	0.017	0.249	0.415	0.424	0.623	3.53%	5.19%
18	1.024	20.943	0.021	0.314	0.524	0.534	0.785	4.45%	6.54%

CONCLUSION

The design, implementation and sustainability of rural electrification projects using stand-alone solar PV modules depends on both technical and social variables. A well-designed solar PV project must first take a macro look at the overarching factors influencing the project viability and sustainability. Project proponents must carefully look at variables affecting project identification (such as where donor investments are most likely to achieve pre-established development goals), the potential for a community organization to carry out the provision of service in the long-term, and the capacity and willingness of the community to pay for the cost of service delivered. Although these non-technical variables are often overlooked by the engineers designing solar PV systems, they form the backbone of a sustainable project.

Once these variables have been defined and analyzed, project proponents (whether they be a donor agency, non-governmental organization or community group) can set about defining the project. They then determine its scope, the energy service provider model to be used, and the energy supply and demand constraints of the community. When selecting a project's scope, the geographical distances and terrain of the project area are important factors. Implementing a project that incorporates a large number of houses with stand-alone solar PV systems may present costs that funders are not willing to bear when better alternatives exist. For example, mini-grid systems may be installed in areas where households are remote but clustered.

Regardless of the system design, some form of community organization must be established. This community organization fosters a sense of community ownership in the project, provides key feedback to the project designers on energy demand (mainly through a household survey), and allows for the selection and training of local technicians. In addition, if the community so decides, this entity may enable the establishment of a community energy service provider, which will locally manage and operate the solar PV systems. While there are a wide range of energy service provider models for these project, incorporating both community organizations and contracted private companies, NRECA recommends the training and establishment of a core of local technicians who can conduct both routine and troubleshooting maintenance. This reduces the cost of service for the local population and eliminates service delays when equipment or systems falter or fail.

A well-designed solar PV project must first take a macro look at the overarching factors influencing the project viability and sustainability.

The selection and design of a solar PV system's components is a relatively straightforward process, but it can be complicated for project proponents with limited technical ability. The principal components of a solar PV system include the solar PV panel, the battery, the charge controller, lamps, outlets, and connecting/mounting hardware. Solar PV systems are dimensioned based upon the daily energy consumption as determined through a household energy survey, the number of days of autonomy required, and the panel capacity, measured in peak watts (Wp). It is important to remember that product quality has a direct impact on project sustainability, but the same is true for maintaining costs within acceptable boundaries. The household energy survey, culminating in the willingness-to-pay and economic benefits analyses, can provide project designers with useful information on the final design parameters for the solar PV systems. Keep in mind that energy supply must match energy demand, along with ability and willingness to pay for the service.

When selecting system components, remember that all the different components interact. The PV module, battery, charge controller, wiring and lighting apparatuses do not operate in isolation. Each must be designed with the others in mind.

Stand-alone solar PV systems have been used in rural electrification programs to great success. A typical rural community's profile often displays a low level of economic development and/or opportunity, low population density, dispersed homes, and a low level of energy consumption. Often, due to the remote location of these communities, they represent low-level priorities within a national or private electricity company's electrification plans, and they may never have access to modern energy services. Under these circumstances, stand-alone solar PV projects provide an efficient, cost-effective, and beneficial development for the community. This is not to say that they are without risk or potential for failure. However, the implementation and operation of solar PV systems through an associated community energy service provider within a rural community can create a level of energy service that provides multiple economic and social benefits. ■